ADVANCED HIGH-POWER MICROWAVE VACUUM ELECTRON DEVICE DEVELOPMENT

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Abstract

The microwave[1] power requirements of particle accelerators have been growing almost exponentially during the last three decades. As a result, economic necessities have been driving the development of microwave vacuum electron devices into three directions:

- Maximizing the power handling capability of any single device;
- Maximizing its overall efficiency;
- Minimizing its manufacturing costs.

This process has sparked a research into a multitude of new devices, as for instance magnicons, relativistic klystrons, super-reltrons and others. The field, however, is still dominated by the classic single-beam klystron, in both its super-power continuous wave and pulsed versions. Power capability and inherent reliability still make it the prime candidate for the majority of currently planned accelerators. Development efforts are therefore directed into further improving its efficiency, but mainly into reducing its costs. Distributed-beam devices, such as the multi-beam klystron (MBK) and the higher-order mode inductive-output tube (HOM-IOT) share a number of properties with the single-beam klystron, but offer the added advantages provided by lower beam voltage.

1 HISTORY

It is always difficult to define when a technological era actually began; thus the author simply claims that the first accelerator projects that required an extraordinary amount of average microwave power were LAMPF at Los Alamos National Laboratory in the early seventies, and a few years later PEP at SLAC and PETRA at DESY. Their demand triggered the development of super-power klystrons especially designed for accelerator use. They are listed in Table 1.

Compared to today's devices these klystrons were not at all optimized regarding performance. Lacking modern software tools, the designers had to approach the target specification through cumbersome cut-and-try procedures. As a result, electron beam focusing usually needed much individual adjustment. The power handling capability of these devices was in many cases stressed to its limits. Conversion efficiency values were with difficulty approaching the 60 % mark. On reaching this mark, beam focusing and operational stability of the CW klystrons became a concern; spurious noise oscillations due to backstreaming electrons created unwanted signals close to the operating frequency. Finally, these devices were expensive. Steps were taken early on to introduce some Design for Manufacturing (DFM), but priority was clearly on the basic issue of making the klystrons work at those unusual power levels. However, after careful adjustment, their life expectancy was usually good, and thus they helped the early high-energy accelerators reach their goals.

Table 1: Early super-power klystrons

Type	Frequency	Power / Pulse width	Source / Accelerator
VA-862A	805 MHz	1.25 MW 1 ms	Varian LAMPF
	353 MHz	350 kW CW	SLAC PEP
YK 1300	500 MHz	600 kW CW	VALVO PETRA

The YK 1300 (Figure 1) is a typical example of those early accelerator klystrons. It not only achieved high efficiency, but also employed features like modular cavity design and air-cooled solenoids for beam focusing, and thus became one of the trendsetters for those devices that represent today's state of the art.

Fig.1: Arrival of the first YK 1300 at DESY (1977)[2]

[1] For the purpose of this paper "microwave" shall apply to frequencies higher than 300 MHz.

[2] Courtesy of Philips Semiconductors

2 STATE OF THE ART

Three distinct categories of klystrons are in use in particle accelerators:

- short-pulse devices, the pulse width varying from several hundred nanoseconds to about 6 microseconds (usually in S-band and higher);
- long-pulse devices with pulse widths around 1 to 10 milliseconds (usually in P- and L-band);
- continuous wave devices (usually in P-band).

2.1 Short-pulse klystrons (μs pulses)

The author believes that the state of the art in this category is best described by characterizing two distinct groups. The first group consists of a class of klystrons similar to those that have originally been developed for the linac of LEP at CERN, but found their application in a number of other linacs, too. Required were klystrons, produced by industry, at 3 GHz with a peak output power of 35 MW and 16 kW average at 4.5 μs pulse width. Two devices were developed and built in competition by TTE and Philips/VALVO. It turned out that both solutions, though different in approach, fully met the specification. Designed in the early eighties, they still represent the state of the art in this class as far as **standard production** types are concerned. A comparable device, though at a lower power level, is produced by Toshiba for the linac at KEK. Not developed by industry, but certainly representing part of the state of the art in large scale production in this class is the 5045 klystron (60 MW peak, 60 kW average power, 3.5 :s pulse width), developed by SLAC in the early eighties.

Table 2: Examples of **standard production** short-pulse klystrons

Type	Frequency	Power / Pulse width	Source
YK 1600	2998 MHz	35 MW 4.5 :s	VALVO (now: EEV)
TH 2094 TH 2100	2998 MHz	35 MW 4.5 :s	TTE
5045	2998 MHz	60 MW 3.5 :s	SLAC

The other group in this class has set its targets even higher. All types in this group have to be considered as **prototype production** or **under development**. The most advanced ones seem to be:

- the klystron developed by SLAC for the SBLC linear collider project at DESY, recently reproduced with some design-for-manufacturing changes by CPI (VKS-8333A, Figure 2). This again is a 3 GHz device, with a peak output power of 150 MW and 27 kW average at a pulse length of 3 μs.

Figure 2: 150 MW short-pulse klystron VKS-8333

Table 3: Examples of **prototype and development** short-pulse klystrons

Type	Frequency / Focusing	Power / Pulse width	Source
	2998 MHz EM	150 MW 3 :s	SLAC
VKS-8333	2998 MHz EM	150 MW 3 :s	CPI
TH 2153	2998 MHz EM	150 MW 1.2 :s	TTE
XL 4	11.4 GHz EM	75 MW 1.2 :s	SLAC
	11.4 GHz PPM	50 MW 1.5 :s	SLAC
E3717	11.4 GHz EM	100 MW 0.5 :s	Toshiba

- an 11.4 GHz klystron, under development in SLAC, for the Next Linear Collider. It has reached 75 MW at 1.2 :s in an electro-magnet, and 50 MW with periodic permanent magnet (PPM) focusing. Presently work concentrates on increasing the power under PPM focusing conditions to 75 MW.

TTE has developed a 3 GHz / 150 MW klystron (TH 2153) for shorter pulses (1.2 :s). Toshiba has 11.4 GHz klystrons under development. Table 3 attempts to summarize the situation.

2.2 Long-pulse klystrons (ms pulses)

There has been little demand for new long-pulse devices in accelerators for quite a period of time, but that has changed drastically in recent years. Projects like TESLA at DESY and SNS at LANL require modern long-pulse klystrons. LANL, requesting 2.5 MW peak / 250 kW average power with 1.7 ms pulse width at 805 MHz, has decided to use single-beam devices. In response, two development projects are on their way, one at CPI and the other one at Litton. DESY requires 10 MW with 1.5 ms pulse width at 1.3 GHz, and a multi-beam klystron (MBK) to cover this specification is in a state of advanced development at TTE. This MBK features 7 beams, thus reducing the beam voltage to 115 kV, rather than the 220 to 230 kV a single-beam klystron would have needed in this application. The device is shown in Figure 3, and Table 4 summarizes the status.

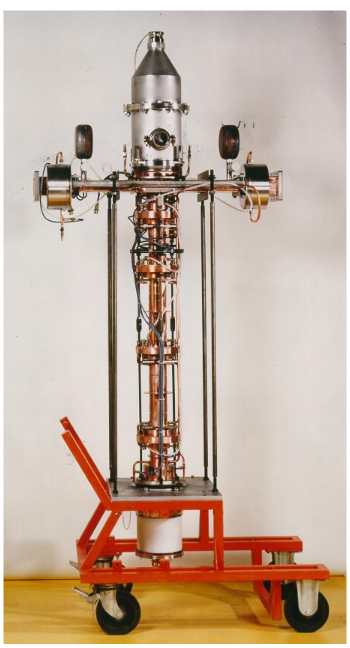

Figure 3: 10 MW long-pulse MBK[3]

Table 4: Examples of long-pulse klystrons under development

Type	Frequency	Power / Pulse width	Source
VKP-8290	805 MHz	2.5 MW 1.7 ms	CPI
	805 MHz	2.5 MW 1.7 ms	Litton
MBK	1.3 GHz	10 MW 1.5 ms	TTE

2.3 CW klystrons

The bulk of activities after the early work for PEP and PETRA has certainly taken place in this category, be it at the accelerator sites, the development laboratories, or on the manufacturing floor. Several frequencies were (and still are) the points of emphasis in this application:

- 352/350 MHz (CERN, LANL)
- ~500 MHz (DESY, Cornell, Daresbury, KEK, ESLS)
- 700 MHz (LANL)
- 2.45 GHz (MAMI)

The state of the art is possibly best described by highlighting some of the devices in these areas. Some typical examples are the 350 MHz / 1.3 MW “work horses”, independently designed and built by VALVO, TTE and EEV. Their excellent stability at high efficiency is shared by a few other “newcomers”: the 500 MHz / 800 kW VKP-7958A and the 700 MHz / 1 MW VKP-7952 (Figure 4). Table 5 tries to provide a survey.

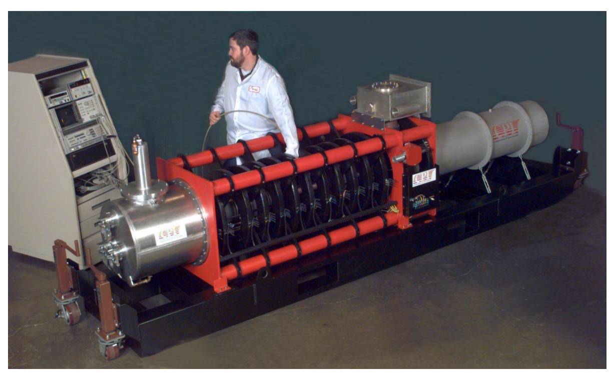

Figure 4: 1 MW CW klystron VKP-7952

[3] Courtesy of Thomson Tubes Electroniques

Table 5: State-of-the-art CW accelerator klystrons (There are numerous other klystrons available, most of them designed for specific applications. The manufacturers should be consulted in all requirement cases).

Type	Frequency	Power	Source
TH 2089B	352 MHz	1.3 MW	TTE
K3513G	352 MHz	1.3 MW	EEV
B-Factory Klystron	476 MHz	1.2 MW	SLAC/ CPI
VKP-7958	500 MHz	800 kW	CPI
E3732	509 MHz	1.2 MW	Toshiba
K3510L	700 MHz	1 MW	EEV
VKP-7952	700 MHz	1 MW	CPI

Compared to the early devices, these modern CW klystrons are considerably improved in three areas.

- **Efficiency**: Most types listed in Table 5 provide efficiency values well beyond 65 %. 67 to 68 % are typical.
- **Beam focusing**: The only individual adjustment needed is typically that of the current through a low power bucking coil.
- **Operational stability**: The early klystron generations were plagued by instabilities in the output signal (spurious oscillation noise) once they reached efficiency levels around 65 %. Numerous investigations and corrections brought some relief, not always in a reliable manner [1]. The majority of the klystrons listed in Table 5 employ means to render the backward flow of electrons, inevitable at high efficiency levels, ineffective.

Lifetime results have to rely on the previous generation of klystrons; they are deemed acceptable. CERN reports that the average lifetime of the first 16 LEP klystrons has reached about 20,000 hours (4 failed during the first 4,000 hours, 5 are still alive after more than 35,000 hours). DESY experienced a similar result with YK 1301 / YK 1304, the predecessors of VKP-7958. Out of 50 klystrons put into service in HERA, 8 died prematurely below 5,000 hours while 7 continue to operate beyond 35,000 hours. Here the average age of 23 living klystrons has reached 23,200 hours.

However, there are still problems to solve.

- **Manufacturing costs**: Efforts in DFM (Design for Manufacturing) are continuing, but some technological break-through is still needed in order to bring the cost of the devices down to a level that permits building the large accelerator structures that are targeted.
- **Beam voltage**: The tendency to concentrate more and more power in single devices has lead to ever increasing beam voltages. This is expensive. It causes not only higher costs for the devices themselves, but also for many things in their periphery: power supplies and modulators, high-voltage insulation, X-ray shielding, buildings (size), environmental protection measures.

3 FUTURE TRENDS

3.1 Improved manufacturability

Cost reduction will have high priority for any high-power vacuum electron device for accelerator application in the future. Design for Manufacturing considerations will not only comprise the use of pre-fabricated materials (like stainless steel tubes for cavity walls, copper pipes for waveguides, threaded rods for support, etc.) like in the past. Attention will also be given to the use of improved manufacturing processes like high-temperature exhaust (to reduce conditioning time) and software-controlled conditioning and test procedures. In addition, large-scale production will be applied where possible.

3.2 Distributed-beam devices

Another point of emphasis will be the development of devices that employ low beam voltage, without compromising but rather enhancing power capability. One category of these devices is the multi-beam klystron (MBK). Beam voltage reductions by a factor in the order of 2 are obtainable this way. So far, MBKs have only been designed for relatively low average power levels, but there is no particular upper threshold in this regard. The example already mentioned in Paragraph 2.2 uses basic-mode cavities.

A further step in the direction of achieving high average power is the transition from basic-mode to higher-order mode (HOM) cavities. The advantage, compared to basic-mode operation, is that the electron beams are no longer in competition with each other for the restricted space in the center of the cavity. Interaction with the outer lobes of an HOM field provides considerably more interaction space, thereby permitting large electron beam cross-sections and correspondingly low space charge density, a vital precondition for high efficiency.

An HOM-IOT (Higher-Order Mode Inductive-Output Tube) is presently under development at CPI. The project is sponsored by Los Alamos National Laboratory (LANL). The specification requires 1 MW CW output power at 700 MHz. The expected results of this development, compared to a klystron having the same specification, are listed in Table 5.

Table 5:
Comparison between HOM-IOT (expected results) and klystron, both operated at 1MW CW / 700 MHz

Device	HOM-IOT	Klystron
Effective efficiency[4]	73 %	60 %
Relative consumption	82 %	100 %
Assembly volume (appr.)	30 cbf	200 cbf
Assembly weight (approx.)	1,000 lbs	5,000 lbs
DC beam voltage	45 kV	90 kV
Gain	25 dB	46 dB

The essentially annular electron beam in this device consists of 25 beamlets, arranged in 5 groups at 5 each. Specific cathode emission density and specific power density in output cavity and collector represent only fractions of the comparable values in the klystron. The drawback, on the other hand, is the HOM-IOT's lower gain.

Figure 5: 1 MW CW HOM-IOT (prototype)

Presently the prototype device is ready for exhaust; test results are expected during summer of 1999.

In a way, the electron beam inside the HOM-IOT can be considered a sheet beam in annular arrangement. Thus the sheet-beam klystron [2], a possible approach to generate the power required for accelerators at very high frequencies, can be regarded a close relative of the HOM-IOT.

[4] For the purpose of amplitude regulation, the klystron has to be operated about 10 % below its power saturation point, while the HOM-IOT (like any IOT) does not saturate at the point of its highest efficiency.

3.3 High efficiency via high voltage

Numerous developments for high-power microwave devices are staying with the high-voltage principle: magnicons [3], relativistic klystrons [4], super-reltrons and others. Sadly, the space available for this paper does not permit to describe the status they have reached so far.

4 ACKNOWLEDGEMENTS

The author wishes to thank

- all those high-energy physicists who demanded more and more microwave power for their projects (and sometimes simply took its availability for granted), thereby triggering the development of modern super-power devices;
- Los Alamos National Laboratory (LANL) for continued support in the development of super-power sources, especially the HOM-IOT;
- all the engineers who worldwide worked on these devices and whose inventiveness, headaches and persistence brought about what is today's state of the art, among them the formidable team at CPI;
- those colleagues who made special contributions to this paper, prominently Michael Ebert (DESY), George Faillon (TTE), Hans Frischholz (CERN) and Saul Gold (SLAC).

Disclaimer

When writing this paper, care has been taken to describe the already restricted range of devices chosen completely enough to give the reader a useful account. Nevertheless, due to the limited size permitted for the paper, and certainly due to limitations in the authors knowledge and resources, the different classes of devices within this range are described through examples only; and perhaps not always by the most striking ones. The author, who has also taken the liberty of excluding devices with less than 10 kW average power from this report, apologizes for any flaws in this respect.

5 REFERENCES

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